BRITISH WELDING

VOL. 7, [illegible] 195[illegible]

WELDING RESEARCH

PRICE FIVE SHILLINGS

* RESEARCH ASSOCIATION

Vol. 7

ISSUE No. 5

BI-MONTHLY

OCTOBER, 1953

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WELDING RESEARCH

29, PARK CRESCENT, LONDON, W.1

ASSOCIATION NOTES

This Journal

After the December issue, *Welding Research* will be discontinued in its present form and in future it will be united with the *Transactions of the Institute of Welding* in a new publication to be known as the *British Welding Journal*. The new journal will be published monthly and will thus provide considerably more space for publication of the results of B.W.R.A. researches, as well as keeping readers more nearly up-to-date.

The technician and the technologist will both be provided for in the *British Welding Journal* and readers will be fully informed of the activities of the professional organisations which represent welding interests in this country. Furthermore there will be bibliographical information, news items about men and matters in the industry and the latest information on the International Institute of Welding.

This amalgamation of *Welding Research* and *Transactions of the Institute of Welding* has only come about through much hard thought and goodwill on both sides. It is hoped that such a co-operative effort will provide further evidence of the intention of both Institutions to work together for the good of the industry which both have the honour to serve.

The *Journal* will consist of approximately 48 pages of technical matter per issue, printed on art paper, and the yearly subscription will be £5.

All nominees of members of the B.W.R.A. will receive one free copy of each issue, further copies being available at the specially reduced rate of 7s. 6d. post free.

Self-Adjusting Arc Process—Practical Improvements

On the following pages of this issue of the *Journal* we are publishing a short note on some work of extremely important practical value concerning the Self-Adjusting Arc Process. This work is being carried out in the laboratories of the Electrical Research Association in conjunction with B.W.R.A. A fully detailed report will be published in the New Year but it was considered that some prior indication should be made of the results so far obtained. No further information, other than that presented in the following note, can be given at the present time, but readers will be fully informed when more details have been released.

THE SELF-ADJUSTING ARC—IMPROVED POWER SOURCES

Researches by the Electrical Research Association in conjunction with the B.W.R.A. show that the degree of self-adjustment is greatly improved for either A.C. or D.C. by using low-voltage power sources. The welding arc has high arc-length stability, and "burn back" troubles can be eliminated. The pre-setting of welding conditions is simplified, since the current is automatically determined by the wire feed rate. Alternatively, the self-adjustment due to conventional power sources can be improved by the addition of an auxiliary self-adjustment control, which can also correct for any drift in power source output.

By J. C. NEEDHAM, B.Sc*., W. G. HULL, A.I.M.,† L. H. ORTON, Ph.D.*

INTRODUCTION

Work of considerable practical significance is in progress at the E.R.A. Laboratories, in collaboration with B.W.R.A. These investigations have for the last few years been primarily concerned with the electrical characteristics of welding arcs in inert atmospheres. Improvements in the A.C. tungsten-arc process, arising from a detailed oscillographic analysis, have already been published.

Subsequent research on the more recently developed self-adjusting arc process has led to a better understanding of arc length "self-adjustment" and shows how this may be improved in practice. A confidential report‡ prepared in 1952 and now released to members of both Associations is awaiting publication. This report deals with the mechanism of arc-length control in the self-adjusting arc, and particularly with the effect of the output characteristics of the power source on the degree of self-adjustment of arc lengths.

The present article draws attention to some of the chief points of interest in this report, and also refers briefly to other matters of practical importance arising in the course of these investigations.

THE SELF-ADJUSTING ARC PROCESS

This is a metal arc process in which the electrode is fed to the arc at a constant rate. In recent years the process has been applied extensively to the welding of a variety of ferrous and non-ferrous materials using a bare electrode and an inert gas to shield the arc and weld pool. In commercial equipment of this type, e.g. "Argonaut," "Aircomatic" and "Sigma," a thin bare-wire electrode is mechanically fed at constant speed through a manually operated welding gun. A high current density, of the order of 50,000 amps. per sq.in., is used which causes the material to be transferred as a spray of small droplets projected at high speed, permitting welding in all positions. At the present time the process is normally operated from a D.C. power source with the electrode positive.

With a constant electrode feed-rate, it is clearly necessary to work under conditions where the arc length is self-adjusting, so that any disturbance of the working length is compensated or corrected by the properties of the arc and its circuit. The mechanism of self-adjustment is illustrated schematically in Fig. 1, which shows how a fall in burn-off rate, due to an increase in arc length, subsequently results in a return to equilibrium conditions at the arc. The converse, of course, occurs for a decrease in arc length.

Two factors contribute towards the change in burn-off rate with arc length. The first is dependent on the output characteristics of the power source, since an increase in arc voltage normally results in a decrease in arc current, and hence in burn-off rate. The second is an inherent property of the arc in which the burn-off rate is less for a long arc than for a short arc at the same current, and is said to be due to the wire electrode tip receiving less radiation from the weld pool at longer arc lengths. This second factor is fixed for given materials. The overall self-adjustment, due to the first factor, can be greatly enhanced by using a power source with a suitable output characteristic.** From Fig. 1 it can be inferred that the larger the decrease in current for a given rise in arc voltage, the greater the self-adjustment and speed of correction.

POWER SOURCE CHARACTERISTICS

Direct Current

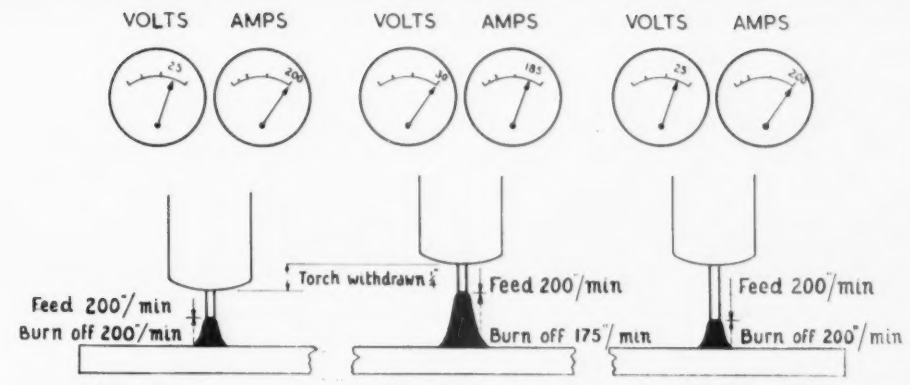
Conventional welding power sources produce virtually constant current conditions because of their steeply drooping

* Electrical Research Association.

† B.W.R.A.

‡ E.R.A. Report Z/T91.

** Patent applied for.



(a) Equilibrium. *Arc length ¼ in., arc voltage 25, arc current 200A.*

(b) Disturbance. *Arc length ½ in., arc voltage 30, arc current 180A with reduced burn-off.*

(c) Correction. *Excess feed reduces arc length to ¼ in., arc voltage returns to 25, arc current to 200A and equilibrium is regained.*

Fig. 1. Illustration of arc length self-adjustment.

output characteristic (see curve 1, Fig. 2). It is seen that the current at a given setting does not vary much with changes in arc voltage. This is suitable for manual metal-arc or automatic welding, where the electrode feed-rate is varied. It is less suitable, however, for self-adjusting arcs in which a large current change for a change in arc voltage is preferable.

With the much flatter output characteristic, as shown in curve 2, Fig. 2, the current change per volt is large, and this is, therefore, a more desirable form of output. It is clear that such a characteristic implies that the power source has basically a low open-circuit voltage which does not differ greatly from the operating arc voltage.

Tests with a low-voltage power source, with a nearly flat characteristic show that in practice a remarkably high degree of self-adjustment is achieved which has a number of advantages. It gives a very steady arc length during welding, any disturbance being rapidly compensated. The trial and error methods of setting the required operating conditions are eliminated since there is no need to set the current to match the wire feed-rate. The operator simply selects the wire feed-rate, and, on striking the arc, the current immediately rises to the value where it consumes the wire at the required rate. Similarly, if the operator wishes to work at a higher current, he merely increases the wire feed-rate which, in turn, demands the heavier current. This applies whatever type of electrode material is used. The improved power source also can eliminate "burn-backs," involving the fusion of the electrode to the guide tube of the torch, which can be experienced with conventional steeply drooping power sources. This may cause considerable delay in production and can readily occur when the wire feed is interrupted if the overall degree of self-adjustment is not high. With the highly self-adjusting circuit, however, when the arc begins to lengthen, the current and the burn-off rate both rapidly fall to zero, before the wire has been burnt back to the guide tube.

With conventional power sources sticking of the electrode into the weld pool can occur on starting if the wire feed is excessive, because the short circuit current delivered does not greatly exceed the working current. As indicated in Fig. 2, however, the short circuit current of the low voltage power source can be sufficiently high to melt the wire electrode and strike an arc.

Alternating Current

In these investigations, self-adjusting arcs have also been run on alternating current. The self-adjustment due to the

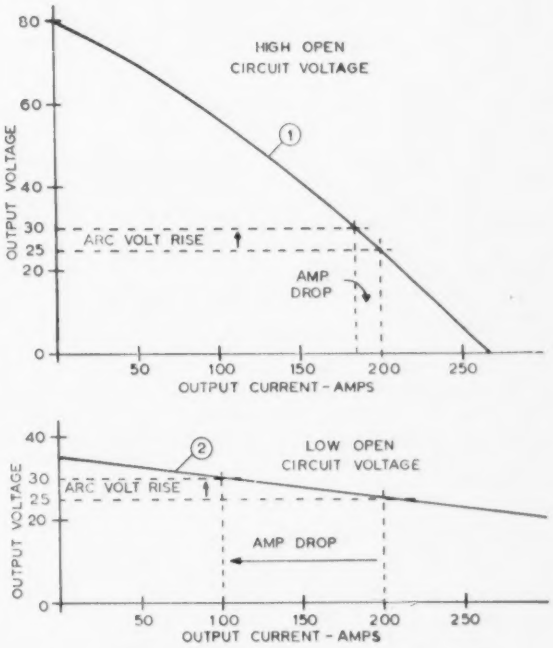


Fig. 2. Output characteristics on D.C.

change of current with arc voltage is very limited (Fig. 3, curve 1) with welding transformers at open-circuit voltages of 80 to 100 v. r.m.s. This figure also shows that at normal arc voltages the output curve is even more steeply drooping than conventional D.C. power sources (Fig. 2, curve 1) of the same open-circuit voltage.

To obtain a preferable output curve (Fig. 3, curve 2) over the welding range for an appreciable degree of self-adjustment, it is again necessary to use a low open-circuit voltage. This raises the problem of regularly reigniting the arc each time the alternating current reaches zero, particularly when using bare-wire electrodes.

The problem is analogous to that of reignition of the A.C. argon arc previously examined by the E.R.A. This information has proved very valuable and in the present work A.C. arcs were successfully stabilised at low open-

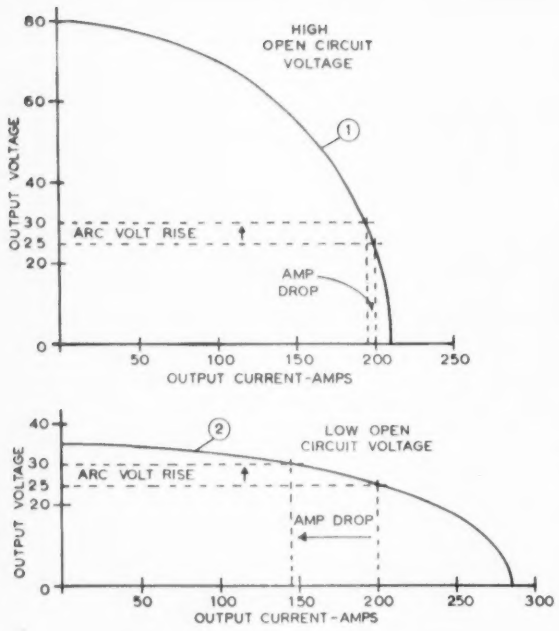


Fig. 3. Output characteristics on A.C.

circuit voltages and showed in practice a high degree of self-adjustment. The units used for arc reignition were modifications of a conventional h.f. spark injector or of the E.R.A. surge injector.[1]

The practical improvements and advantages, resulting from the high self-adjustment obtained with A.C. power source of low, open-circuit voltage, were similar to those for the D.C. source.

Superposed Self-Adjustment

The limited self-adjustment associated with the steeply drooping power source of conventional design may be improved by superposing on the power circuit a control based on the arc conditions, and may be applied to both A.C. and D.C. welding.*

If the current as set by the operator is too high for the wire feed rate used, then the control can effect a reduction in current until the desired equilibrium is achieved. Similarly, if the arc voltage is initially less than required, the control can operate to increase the circuit current, and hence the burn-off rate and arc length. This also means that the control can hold the arc at a preset and constant voltage, irrespective of the wire feed-rate used or initial current settings.

There are numerous alternative control systems according to the specific application and the type of power source. For example, the superposed self-adjustment control can be applied direct to or be incorporated in the power source itself, or can take the form of an auxiliary unit connected into the external welding circuit, thus leaving the conventional power source unaltered.

The overall self-adjustment achieved using the superposed control is not unlimited, and the control may not necessarily operate in time to prevent burn-backs or electrode sticking if the original welding conditions are grossly mismatched. The control systems developed have shown, however, to effect a marked improvement in self-adjustment and to facilitate the operation of the process in practice.

Drift Eliminator

A trouble often experienced when the overall self-adjustment is limited is that of "drift." Thus, even when the operator by trial and error methods has obtained the correct current setting for the wire feed at the desired arc length, the arc length or voltage can then gradually drift as a result of changes in the output of the power source, due to warming up of the windings or changes in mains voltage.

With the low voltage power source, or using the superposed control referred to above, the high self-adjustment automatically corrects for drift. Where the self-adjustment is so limited, however, that drift is noticeable, it can be corrected or compensated for by a simple control** which need not be applied to the power source, but can operate on the welding unit itself. This control can again hold the arc at a preset voltage once the operator has established the arc.

* Patent applied for.

** Patent applied for.

REFERENCE

[1]Needham, J. C., and Orton, L.H. "A.C. Argon Arc Welding at Less than 50 v. r.m.s. Open Circuit," *Trans. Inst Welding*, **15** (6), December, 1952, pp. 161-165.

VANADIUM-BEARING HIGH TENSILE WELDABLE STEELS

This report is part of a programme of research work on the possible replacement of Molybdenum by Vanadium for high tensile steels. The British Welding Research Association has investigated the weldability of these special steels and the results are published in the next article of this issue of the journal.

By Staff of B.S.A. Group Research Centre, Sheffield

INTRODUCTION

The British Welding Research Association has carried cut a considerable amount of research work[1] in the development of high-tensile weldable steels. As a result of this work, two steels have been selected[2] which combine good weldability with satisfactory mechanical properties in the normalised and in the normalised and tempered conditions, at the section sizes investigated. Both steels are alloyed with manganese, nickel, chromium and molybdenum; the actual chemical compositions are given in Table I (steels A and B).

In reaching these two steels, the effects of variations in Mn, Ni and Cr contents had been studied, but the Mo content had been maintained throughout at a constant value of 0·25 per cent. It was suggested by the B.S.A. Group Research Centre that Mo could be effectively replaced by other alloying elements, notably vanadium, and that the effects of this substitution should be studied in view of existing and possible future difficulties in the world supply of molybdenum. This suggestion was accepted and the B.S.A. Group Research Centre undertook to prepare suitable experimental melts of V-bearing steels, to investigate their mechanical properties, and to supply material for weldability tests to be carried out by B.W.R.A.

This report describes the preparation of the experimental steels, their heat treatment and their mechanical properties.

MATERIALS

The six specifications for experimental melts based on the two steels A and B, with the Mo contents omitted or reduced, and with suitable additions of V, are shown in Table I.

Three 20-lb. high-frequency furnace melts were made to each of the six specifications, and a single 14 lb. ingot cast from each melt. The chemical compositions of the eighteen ingots are given in Table II.

There were rather wide variations in these compositions, but it was decided to proceed with the further examination of the steels. Two ingots from each set of three were forged to plate 4 by $\frac{3}{8}$ in. thick for weldability testing, and the third to $1\frac{1}{4}$ in. diameter bar. These two section sizes are equivalent in that they cool at similar rates (according to B.S.971, $\frac{3}{8}$ in. thick plate is equivalent to 1·23 in. diameter bar, in air cooling).

EXPERIMENTAL WORK

Heat Treatment and Mechanical Properties of Bar Material

Each $1\frac{1}{4}$ in. diameter bar was cut into four sections, of which two were designated X and two Y. All the bar material was then heat treated as follows:

Bars X—Normalise from 900 deg. C., Temper at 500 deg. C. for 1 hour.

Bars Y—Normalise from 900 deg. C., Temper at 650 deg. C. for 1 hour.

The bars were allowed to air cool from the tempering temperature in order to check on the possibility of temper brittleness in the absence of molybdenum.

The results of mechanical tests are given in Table III.

The steels A and B, on which these six vanadium-bearing steels are based, were intended to have an 0·2 per cent. proof stress of not less than 30 tons/sq.in. in the normalised and tempered condition. The data in Table III show that this

Table I.—Six Specifications for Vanadium-Bearing Steels based on Steels A and B (Wt. per cent.)

Specification Ref.	C	Mn	Si	S	P	Ni	Cr	Mo	V
Steel A	0·13—0·17	0·80—1·0	0·3 max.	0·035 max.	0·035 max.	0·5—0·7	0·8—1·0	0·20—0·25	—
1A	,,	,,	,,	,,	,,	,,	,,	—	0·15
2A	,,	,,	,,	,,	,,	,,	,,	—	0·10
3A	,,	,,	,,	,,	,,	,,	,,	0·10	0·10
Steel B	,,	1·0—1·2	,,	,, max.	,, max.	0·2 max.	0·5—0·7	0·20—0·25	—
1B	,,	,,	,,	,,	,,	,,	,,	—	0·15
2B	,,	,,	,,	,,	,,	,,	,,	—	0·10
3B	,,	,,	,,	,,	,,	,,	,,	0·10	0·10

Table II.—Chemical Compositions of all Experimental Steels

Specification Ref.	Cast Ref.	C	Mn	Si	S	P	Ni	Cr	V	Mo
1A	1	0·12	0·57	0·11	0·021	0·012	0·75	0·87	0·22	—
1A	2	0·17	0·69	0·11	0·021	0·010	0·70	0·90	0·22	—
1A	3	0·16	0·69	0·10	0·025	0·010	0·76	0·89	0·23	—
2A	4	0·15	0·78	0·09	0·025	0·010	0·73	0·92	0·14	—
Type A 2A	5	0·18	0·74	0·05	0·021	0·010	0·83	0·88	0·14	—
2A	6	0·19	0·90	0·05	0·021	0·011	0·83	0·90	0·12	—
3A	7	0·16	0·86	0·18	0·018	0·010	0·79	0·97	0·14	0·19
3A	8	0·17	0·99	0·20	0·021	0·010	0·78	0·95	0·14	0·19
3A	9	0·17	0·85	0·13	0·028	0·010	0·75	0·96	0·10	0·21
1B	10	0·20	1·24	0·16	0·025	0·010	0·10	0·71	0·23	—
1B	11	0·17	1·23	0·15	0·021	0·010	0·10	0·70	0·19	—
1B	12	0·16	1·13	0·15	0·020	0·010	0·08	0·68	0·20	—
2B	13	0·15	1·21	0·16	0·022	0·010	0·14	0·68	0·18	—
Type B 2B	14	0·13	1·13	0·14	0·024	0·011	0·12	0·69	0·12	—
2B	15	0·15	0·97	0·17	0·022	0·011	Trace	0·62	0·13	—
3B	16	0·16	1·08	0·06	0·022	0·010	,,	0·69	0·15	0·15
3B	17	0·15	1·13	0·13	0·022	0·010	,,	0·62	0·13	0·13
3B	18	0·15	0·94	0·09	0·023	0·010	,,	0·68	0·12	0·17

Table III.—Mechanical Properties of Six Vanadium-Bearing Steels (Bar material)

Specification Ref.	Cast Ref.	Heat Treatment Ref.	Yield Point (0·2 per cent. Proof) (tons per sq.in.)	Maximum Stress (tons per sq.in.)	Elongation (per cent.)	Reduction in Area (per cent.)	Izod Impact (ft./lb.)
1A	3	X	32·0	41·6	28·0	61·6	62, 57, 80
		Y	30·4	39·6	29·0	64·0	70, 73, 35
Type A 2A	6	X	33·6	44·0	25·0	57·2	44, 70, 40
		Y	33·6	43·2	24·0	61·6	57, 66, 73
3A	9	X	34·0	44·7	21·0	50·0	35, 27, 26
		Y	36·4	44·8	22·0	59·6	76, 76, 73
1B	12	X	29·6	39·6	30·0	66·0	85, 88, 92
		Y	29·6	38·0	30·0	72·5	91, 92, 98
Type B 2B	15	X	26·0	35·2	35·0	72·5	96, 94, 92
		Y	26·0	34·0	35·0	72·5	95, 97, 96
3B	18	X	27·6	36·0	30·0	66·0	85, 83, 82
		Y	29·2	36·4	30·0	66·0	85, 93, 93

Table IV.—Mechanical Properties of all casts of Experimental Steels (check test on bar and plate)

Specification Ref.	Cast Ref.	Material	0·2 per cent Proof Stress tons/sq.in.	Ultimate Tensile Stress tons/sq.in.	Elongation (per cent.)	Reduction of Area (per cent.)
1A	1	plate	28·0	37·2	35	72
	2	,,	35·0	43·6	32	70
	3(Y)	bar	30·4	39·6	29	64
2A	4	plate	33·3	41·3	34	70
Type A	5	,,	32·4	43·2	31	70
	6(Y)	bar	33·6	43·2	24	61·6
3A	7	plate	42·6	50·6	26	67
	8	,,	45·2	54·0	22	64
	9(Y)	bar	36·4	44·8	22	59·6
1B	10	plate	32·1	42·3	31	67
	11	,,	32·4	41·6	29	70
	12(Y)	bar	29·6	38·0	30	72·5
2B	13	plate	29·2	38·2	36	72·5
Type B	14	,,	27·7	35·3	41	75
	15(Y)	bar	26·0	34·0	35	72·5
3B	16	plate	35·2	43·8	29	70
	17	,,	34·9	42·0	34	72
	18(Y)	bar	29·2	36·4	30	66

strength level is maintained in steel A when vanadium is substituted for molybdenum and even when the vanadium content is reduced to 0·12 per cent. In steel B, on the other hand, the 0·2 per cent. proof stress falls to 29·6 tons/sq.in. when a direct replacement of vanadium for molybdenum is made, and to 26·0 tons/sq.in. when a reduced vanadium content is used.

The ductility of all the steels is good in relation to their strength, and the Izod impact value at room temperature is also very high, except in specimens 6X and 9X.

In general the specimens tempered at 650 deg. C. tended to be better in yield/ultimate ratio, ductility and toughness than those tempered at 500 deg. C.

Heat Treatment and Mechanical Properties of Plate Material

The plate material was all heat treated by normalising at 900 deg. C., and tempering at 650 deg. C. for one hour, air cooling after tempering. Because of the variations in chemical composition in the experimental steels, it was decided to carry out check mechanical tests on samples cut from the heat treated plates. The results are given in Table IV, with data from Table III on bar material with the same heat treatment as the plate.

When due allowance has been made for composition variations, in particular with respect to carbon content, it is clear that the plate material exhibits higher values of proof stress and ultimate tensile stress than the bar material. This could be due to the different forging conditions, since the plate material was subjected to a greater degree of hot work than was the bar material. However, a further possible cause of variation was in the microstructure produced by heat treatment.

Microscopic Examination

Samples of all eighteen steels were taken from the heat treated test specimens after mechanical testing, care being taken to select specimens which had not been cold worked in the testing process. These samples were polished and etched in 2 per cent. nital and the structures were examined under the microscope.

Table V.—Relationship between Microstructure, Carbon Content and 0·2 per cent Proof Stress of the Experimental Steels

Specification Ref.		Cast Ref.	Material	Micro-structure	Carbon Content (per cent)	0·2 per cent. Proof Stress (tons/sq.in.)
Type A	1A	1	plate	F + P	0·12	28·0
		2	,,	F + P	0·17	35·0
		3(Y)	bar	F + P	0·16	30·4
	2A	4	plate	F + P + M	0·15	33·3
		5	,,	F + P + M	0·18	32·4
		6(Y)	bar	F + M	0·19	33·6
	3A	7	plate	M + F	0·16	42·6
		8	,,	M + F	0·17	45·2
		9(Y)	bar	F + M + P	0·17	36·4
Type B	1B	10	plate	F + M + P	0·20	32·1
		11	,,	F + P + M	0·17	32·4
		12(Y)	bar	F + P	0·16	29·6
	2B	13	plate	F + P + M	0·15	29·2
		14	,,	F + P + M	0·13	27·7
		15(Y)	bar	F + P + M	0·15	26·0
	3B	16	plate	F + M	0·16	35·2
		17	,,	F + M	0·15	34·9
		18(Y)	bar	F + M + P	0·15	29·2

F = Ferrite M = Tempered martensite P = Pearlite or troostite

The microstructures were varied, but all showed ferrite as a major constituent. The carbide phase was present either as a fine pearlite or troostite or as tempered martensite; both were present in some cases, in varying proportions. The actual grain size was considerably smaller in the specimens taken from plate than in those taken from bar, confirming the greater degree of hot work. The microstructures are given in Table V together with the carbon content and proof stress of the corresponding test pieces.

Typical microstructures are shown in Figs. 1-6, all photographed at 1000 magnifications. Fig. 1 is typical of plate material, Fig. 2 of bar material, both having a ferrite-pearlite structure; the much smaller grain size of the former is apparent. Referring to Table V, it is clear that this grain size difference must account for the lower proof stress of the bar material, in those cases where the microstructures are the same (Specifications 1A and 2B).

Fig. 3 shows an intermediate microstructure of ferrite

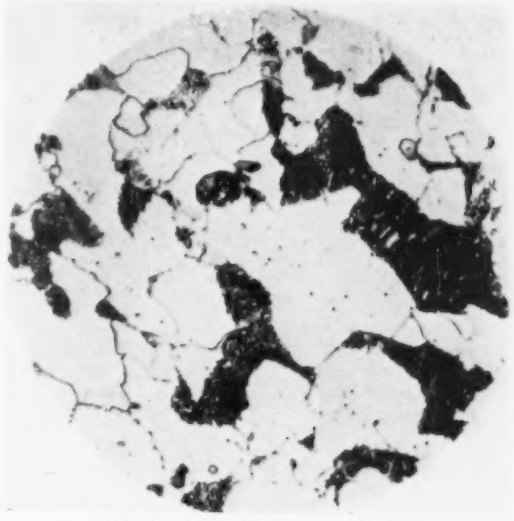


Fig. 1. Cast reference 2. ×1000

Fig. 2. Cast reference 3(Y). ×1000.

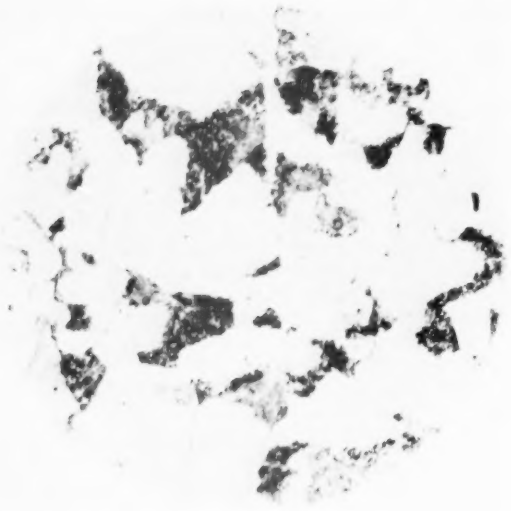


Fig. 3.—Cast reference 4. ×1000.

Fig. 5. Cast reference 5. ×1000.

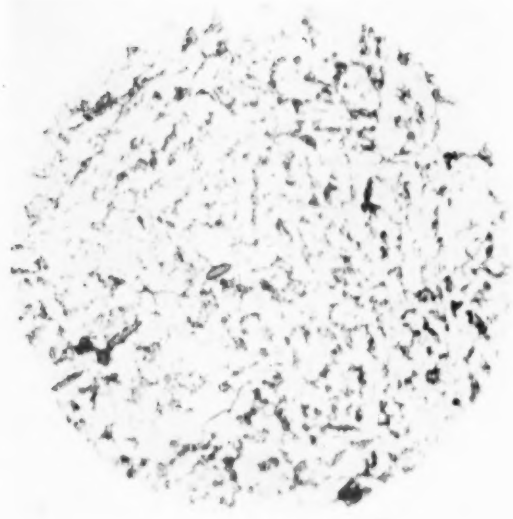


Fig. 4. Cast reference 8. ×1000.

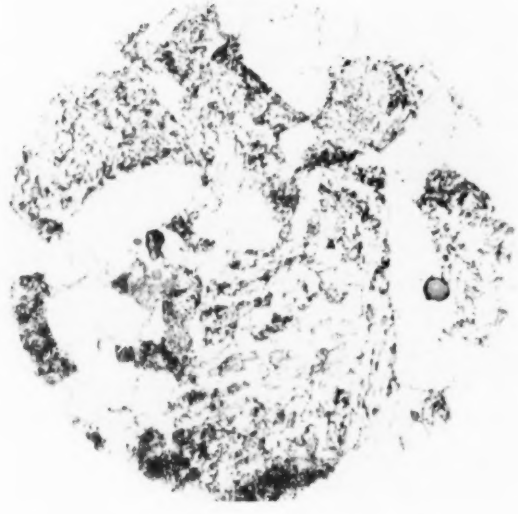


Fig. 6. Cast reference 6.(Y) ×1000.

plus pearlite and some tempered martensite, and Fig. 4 a microstructure in which tempered martensite predominates. In general, where some martensite is formed, the tendency is for the plate material to contain more than the corresponding bar material. This difference may be due to slightly faster cooling rates in the plate than in the bar, but the finer grain size may also have had some influence. Thus the lower proof stress of the bar material may be explained on these grounds, namely, a coarser grain size and a tendency to harden to a smaller degree than the plate material. An anomalous result occurred in Specification 2A, in which the bar material hardened more than the corresponding plate. The two microstructures are shown in Fig. 5 (plate) and Fig 6 (bar). This anomaly may be due to some accident in the normalising of the bar, but it is significant that although the proof and ultimate stress values for this bar are high, the ductility is comparatively low, as can be seen by reference to Table IV.

DISCUSSION

It is perhaps unfortunate that with the section sizes and the cooling conditions used to produce the materials required for these experiments, the steels should have such an alloy content that some have given a hardened structure, others a ferrite-pearlite structure, and the rest have given an intermediate structure. These variations in microstructure have to some extent obscured the significance of the results.

The original steels A and B, heat treated under comparable conditions, gave 0·2 per cent. proof stress values of 31·2 tons/sq.in. and 29·7 tons/sq.in. respectively. If we compare these results with those on the two groups of experimental steels, 1 to 9 and 10 to 18 respectively, the following general conclusions can be drawn:—

(*a*) The replacement of Mo by the same amount of V causes some improvement of mechanical properties in both Steel A and Steel B.

(*b*) The replacement of Mo by less V gives equivalent properties in Steel A and lower properties in Steel B.

(*c*) The partial replacement of Mo by V gives an improvement in both Steel A and Steel B.

If the cooling rate of the steels was reduced by heat treating larger sections, the formation of martensite would be suppressed and the pearlite structure would be coarsened. The undoubted effect of this would be to reduce the mechanical properties of the steel.

It is considered, particularly in the U.S.A., that the mechanical properties of a hardenable steel are dependent on its alloy content and microstructure. The difference in 0·2 per cent. proof stress between Cast Ref. 2 (35·0 tons/sq.in.) and 8 (45·2 tons/sq.in) each with 0·17 per cent. carbon is very significant. The drop in properties will be marked as the microstructure changes from martensitic to pearlitic, and much more gradual as the pearlitic structure becomes coarser. It is to be expected therefore that if these steels are normalised in larger section sizes, the proof stress values will fall. However, in the heat-affected zone of a weld, the cooling rates will be much higher. Hence the microstructure of the heat-affected zone is likely to be largely martensitic, since the steels have been shown to be on the verge of full hardening even when air cooled. Therefore the heat-affected zone hardness and the weldability of these steels will not necessarily correlate with the mechanical properties. At more rapid cooling rates the steels will in fact develop much higher mechanical properties than are produced by the normalising and tempering treatment considered here.

CONCLUSIONS

1. In a normalised and tempered weldable steel containing 0·15 per cent. C, 0·9 per cent. Mn, 0·6 per cent. Ni, 0·9 per cent. Cr, and 0·22 per cent. Mo, the Mo can be replaced by a smaller amount (about 0·14 per cent.) of V with no loss in proof stress.

2. In a normalised and tempered weldable steel containing 0·15 per cent. C, 1·1 per cent. Mn, 0·2 per cent. max. Ni, 0·6 per cent. Cr and 0·22 per cent. Mo, the Mo can be replaced by the same amount of V with no loss in proof stress.

3. There is no evidence of temper brittleness in such steels when air cooled from the tempering temperature.

4. When normalised in the form of 1¼ in. diameter bars, or $\frac{5}{8}$ in. thick plates, the steels are on the verge of air hardening. Apart from ferrite, the microstructures contain pearlite, or martensite, or both. This variation in microstructure is responsible for the variation in the mechanical properties. The proof stress is much higher than the minimum required, when the structure contains much martensite.

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WELDABILITY OF TWELVE LOW-ALLOY STEELS CONTAINING VANADIUM

By B. J. Bradstreet, B.Sc.

SYNOPSIS

Weldability tests have been made on twelve vanadium-bearing low-alloy steels to determine their susceptibility to hard-zone cracking. The twelve steels now reported have the same basic composition as two weldable Mn-Ni-Cr-Mo steels tested previously, with the molybdenum partially or completely replaced by vanadium. The steels have been tested with the B.W.R.A. Controlled Thermal Severity Test assembly, using mild steel electrodes with a low-hydrogen type coating.

INTRODUCTION

As described in the foregoing report, the B.S.A. Group Research Centre prepared twelve experimental vanadium-bearing steels in the form of $\frac{5}{8}$ in. thick plate for weldability tests.

The weldability of the steels was assessed in terms of the resistance to crack formation in the heat-affected zone adjacent to a restrained weld under controlled conditions of cooling.

TEST EMPLOYED

To assess the weldability of the steels, the B.W.R.A. Controlled Thermal Severity (C.T.S.) test was used. This test, which has been described previously,[1] makes it possible to simulate the cooling conditions occurring in any type of structural joint.

In the present tests, three grades of cooling severity were chosen, with Thermal Severity Numbers (as defined previously[1]) of 4, 6 and 14,* the last of these representing conditions of cooling as severe as those occurring in most types of structural joint. Severities of T.S.N. 4 and T.S.N. 6 were obtained using ½-in. thick top and bottom plates; T.S.N. 14 was obtained with a ½-in. top plate on a 1½ in. bottom plate, using only the trithermal weld position.

The top plates for the tests were machined from the experimental steels, and the bottom plates were all made from steel A, since there was not sufficient material available from the experimental casts to provide complete C.T.S. assemblies.

MATERIALS

The twelve experimental steels were made in 20 lb. high-frequency induction-furnace melts. Each ingot was forged to a plate approximately 15 by 4 by ⅝ in., and these plates

* Owing to the great difference in plate thickness, tests with a nominal severity of T.S.N.14 probably had a true severity of about T.S.N.12.

Table I.—Cast Analyses of Experimental Steels

Cast Ref.	C per cent.	Si per cent.	S per cent.	P per cent.	Mn per cent.	Ni per cent.	Cr per cent.	V per cent.	Mo per cent.
1	0·12	0·11	0·021	0·012	0·57	0·75	0·87	0·22	—
2	0·17	0·11	0·021	0·010	0·69	0·70	0·90	0·22	—
4	0·15	0·09	0·025	0·010	0·78	0·73	0·92	0·14	—
5	0·18	0·05	0·021	0·010	0·74	0·83	0·88	0·14	—
7	0·16	0·18	0·018	0·010	0·86	0·79	0·97	0·14	0·19
8	0·17	0·20	0·021	0·010	0·99	0·78	0·95	0·14	0·19
10	0·20	0·16	0·025	0·010	1·24	0·10	0·71	0·23	—
11	0·17	0·15	0·021	0·010	1·23	0·10	0·70	0·19	—
13	0·15	0·16	0·022	0·010	1·21	0·14	0·68	0·18	—
14	0·13	0·14	0·024	0·011	1·13	0·12	0·69	0·12	—
16	0·16	0·06	0·022	0·010	1·08	Trace	0·69	0·15	0·15
17	0·15	0·13	0·022	0·010	1·13	Trace	0·62	0·13	0·13
A	0·14	0·18	0·032	0·017	0·89	0·56	0·93	—	0·22
B	0·14	0·30	0·027	0·016	1·14	0·23	0·66	—	0·24

were then normalised from 900 deg. C., followed by tempering at 650 deg. C. for one hour.

The cast analyses of the twelve steels, together with those of steels A and B, are given in Table I.

The bottom plates of the test assemblies were all made with plate from the 2-ton cast of steel A.

Mild steel, 8 s.w.g. electrodes, B.S.1719 classification E.614, were used for all test welds; these electrodes are especially recommended for the welding of low-alloy steels. All the electrodes were taken from the same batch, to maintain uniform test conditions.

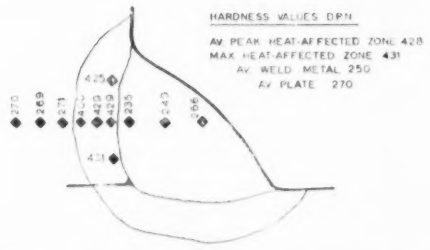

Fig. 1. Positions of hardness impressions. Values are for steel 8, T.S.N. 14.

EXPERIMENTAL PROCEDURE

Method of Making Test Welds

The method of preparing the C.T.S. assemblies, and the testing procedure, have been fully described elsewhere.[2] The electrodes were heated in an air-circulating oven at 110 deg. C. for a minimum of one hour immediately before use. Test welds were all made in the flat position with the assembly held at 45 deg. to the horizontal in a heat-insulated jig, and with the plates initially at room temperature.

The electrodes were marked so that 4 in. of electrode was used for each 3 in. test weld. All welds were made with alternating current, under approximately the same conditions, the following figures being typical:

Open-circuit voltage	105 volts
Arc voltage	22 ,,
Welding current	178 amp.
Time of welding	26 sec.
Energy input	28,000 joules per in.

Sectioning and Examination of Welds

To allow adequate time for the formation of hard-zone cracks,[3] no welds were sectioned until at least a week after welding.

Each test weld was sectioned to provide three specimens, which were polished and etched. Crack lengths in these sections were expressed as a percentage of the length of the fillet leg in which they occurred. Diamond pyramid hardness tests were made with a 10 kg. load on the centre section of each test weld, as shown in Fig. 1.

EXPERIMENTAL RESULTS

The results of the tests are shown in Table II.

Since only the top plate of each assembly was made from the steel under test, it was only intended to measure crack lengths in the vertical leg of each weld. In the tests, however, no cracks occurred in the horizontal leg of any of the welds. This confirmed the excellent weldability of steel A, as mentioned in the footnote to Table III.

No cracks occurred on any of the welds made with $\frac{1}{2}$ in. bithermal flow (T.S.N.4), even with steel 8, which had an average plate hardness of 259 D.P.N. and a maximum hardness in the heat-affected zone of 413 D.P.N.

On two of the steels, cracks occurred in specimens welded with both T.S.N.6 and T.S.N.14; on seven of the steels, cracks occurred with T.S.N.14 only; three of the steels showed complete absence of cracking.

There was a general increase of crack severity with plate hardness, and also with the hardness in the heat-affected zone, but no definite relationship could be established in view of the limited number of results available with each test severity.

A photomacrograph of one of the weld sections is shown in Fig. 2. The crack has "forked," giving the appearance of two distinct overlapping cracks in the section illustrated.

DISCUSSION

A brief summary of the results of all the tests is given in Table III.

The best combination of weldability and mechanical properties was given by steel 2, which had a yield stress of 35 tons per sq.in.; only very slight cracking occurred on one section of the weld made with T.S.N.14 on this steel. Steel 4, with a similar composition, gave a slightly lower yield stress with complete absence of cracking. These two steels were both based on steel A; they have higher mechanical properties than steel A, but the tests indicate that they have slightly inferior weldability.

Table II.—Details of Fillet Size, Hardness and Cracking

Steel No.	T.S.N.	Average Leg Length (in.)	Hardness D.P.N. (10 kg. load)		Average Cracking in Vertical Leg (per cent.)
			Average Peak in Heat-affected Zone	Average plate	
1	4	0·24	277	176	nil
	6	0·26	297	174	nil
	14	0·24	329	176	nil
2	4	0·25	331	198	nil
	6	0·26	368	198	nil
	14	0·25	371	193	< 1
4	4	0·24	349	190	nil
	6	0·23	356	183	nil
	14	0·23	381	181	nil
5	4	0·24	353	199	nil
	6	0·24	394	199	nil
	14	0·22	413	208	4
7	4	0·25	389	229	nil
	6	0·23	405	230	nil
	14	0·23	410	244	47
8	4	0·24	409	259	nil
	6	0·24	421	265	76
	14	0·24	428	270	71
10	4	0·23	368	185	nil
	6	0·25	405	187	73
	14	0·24	417	188	23
11	4	0·24	350	189	nil
	6	0·23	369	188	nil
	14	0·24	385	185	2
13	4	0·25	312	171	nil
	6	0·26	355	166	nil
	14	0·25	381	180	33
14	4	0·25	297	160	nil
	6	0·25	316	158	nil
	14	0·22	347	161	nil
16	4	0·28	336	212	nil
	6	0·23	397	210	nil
	14	0·24	403	201	76
17	4	0·25	329	198	nil
	6	0·23	355	189	nil
	14	0·24	387	199	28

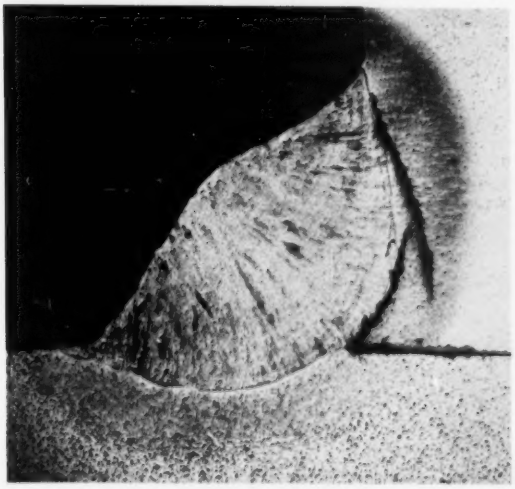

Fig. 2. Crack in heat-affected zone Steel 16, T.S.N. 14.

Steel 7 was also interesting, in that it had a yield stress (or 0·2 per cent. proof stress) of 42·6 tons per sq.in., and yet did not crack on the ½-in. trithermal assembly (T.S.N.6).

It would appear that the molybdenum content of steel A (0·22 per cent.) could be replaced by about 0·15 per cent. vanadium, producing a steel with a yield stress in the region of 34 tons per sq.in. in the normalised and tempered condition, with good weldability when using electrodes with a low-hydrogen type coating.

CONCLUSIONS

1. The replacement of molybdenum by vanadium in a low-alloy steel such as steel A improves the mechanical properties of the steel in the normalised and tempered condition without unduly affecting the good weldability when using low-hydrogen electrodes.

2. The steel which gave the best combination of weldability and mechanical properties was one containing approximately 0·17 per cent. carbon, 0·7 per cent. manganese, 0·7 per cent. nickel, 0·9 per cent. chromium, and 0·22 per cent. vanadium, with a yield stress of 35 tons per sq.in. when normalised and tempered in the form of ½-in. thick plate.

Table III.—Summary of Results

Steel No.	Basic Composition	C per cent.	V per cent.	Mo per cent.	Yield Stress or 0·2 per cent. Proof Stress (tons per sq.in.)	T.S.N.*	Average Peak Hardness in Heat-affected Zone (D.P.N.)	Average Cracking in Vertical leg (per cent.)
1	Steel A	0·12	0·22	—	28·0	14	329	nil
2	,,	0·17	0·22	—	35·0	6 14	368 371	nil <1
4	,,	0·15	0·14	—	33·3	14	381	nil
5	,,	0·18	0·14	—	32·4	6 14	394 413	nil 4
7	,,	0·16	0·14	0·19	42·6	6 14	405 410	nil 47
8	,,	0·17	0·14	0·19	45·2	4 6 14	409 421 428	nil 76 71
10	Steel B	0·20	0·23	—	32·1	4 6 14	368 405 417	nil 73 23
11	,,	0·17	0·19	—	32·4	6 14	369 385	nil 2
13	,,	0·15	0·18	—	29·2	6 14	355 381	nil 33
14	,,	0·13	0·12	—	27·7	14	347	nil
16	,,	0·16	0·15	0·15	35·2	6 14	397 403	nil 76
17	,,	0·15	0·13	0·13	34·9	6 14	355 387	nil 28
Steel A		0·14	—	0·22	31·2	18	388	6†
Steel B		0·14	—	0·24	29·7	(Reeve test)	428	5†

* The test results are not all quoted in this table. No cracking occurred on tests conducted with lower Thermal Severity numbers than those listed for each steel. Owing to the great difference in plate thickness, tests with a nominal severity of T.S.N.14 probably had a true severity of about T.S.N.12.

† The welding tests on steels A and B were conducted on a Reeve test assembly, using class E.217 electrodes, producing very severe test conditions. With the conditions under which steels 1-17 were welded, no cracking would be expected on Steels A and B.

ACKNOWLEDGMENTS

The valuable discussion on the work, given by members of the High Tensile Weldable Structural Steel Investigation Steering Committee of the Ministry of Supply, is gratefully acknowledged.

Thanks are also due to the B.S.A. Group Research Centre for supplying the experimental steels, for the cast analyses, and for mechanical test results on the steel.

The author gratefully acknowledges the help given to him during the investigation by Dr. C. L. M. Cottrell of the B.W.R.A.

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TRIPLE-PROJECTION WELDING

—OF DEEP DRAWING MILD-STEEL SHEET

Previous work on single-projection welding has already been published by the Association and this report FR. 3/64 gives further results from a very comprehensive programme on projection welding. The work is now being prepared for publication as a B.W.R.A. technique memorandum on projection welding and the booklet will be available shortly.

By J. E. ROBERTS, M.Eng., A.I.M.

SYNOPSIS

Specimen welds, in 14, 16, 18 and 20 s.w.g., were tested for total shear strength, and it was found that strengths equal to three times that of a single projection could be made when projections were at 2 in. pitch. At smaller pitches, some reduction in the maximum strength obtainable is unavoidable. This reduction, for a pitch of 1 in. in 14 s.w.g., is approximately 25 per cent. of the strength at 2 in. pitch; the reduction is less for the thinner gauges of material. At 1/2 in. pitch, the three welds grow together to form a single weld, with a considerable drop in strength. The use of three separate projections at $\frac{1}{2}$ in. pitch is not recommended. Weld quality has been assessed by strength, consistency of strength (measured by the coefficient of variation), and weld appearance. Recommended welding conditions are given at the end of the report.

INTRODUCTION

The object of the experiments was to determine whether a group of three projection welds could be made with a consistent strength when tested as a complete joint, and the relationship of that group strength to the strength of a single weld made at the optimum conditions.

Previous Work on Single Projections

The first stage of the programme, on single-projection welds, covered a comprehensive study of the mechanical properties of projections of various shapes to determine the most satisfactory contour, the maximum usable electrode load, and the optimum welding conditions for the single projection. The results have already been published[1] and a summary is presented in Table I. These results are a basis of comparison for the properties of the triple-projection welds and for preliminary selection of the welding conditions for triple welds.

Table I.—Optimum Conditions for Welding Single Projections.

Sheet Thickness (S.W.G.)	*Electrode Load (lb.)	*Electrode Load (lb./sq. in. on projection root)	Welding Current (kA)	Weld Time (Cycles, 50 c.p.s.)	Shear Failing Load (tons)	Coefficient of variation
14	500	17,250	12·2	35	1·67	2·1
16	350	15,800	11·2	30	1·38	4·6
18	300	18,400	9·2	20	0·75	4·5
20	200	12,300	8·1	20	0·42	—

* The load is the maximum allowable if cold projection collapse is to be less than 10 per cent.

WELDING MACHINE, MATERIALS, SPECIMEN TYPE AND TESTING METHODS

The welding of the triple-projection specimens was done on a 100 kVA projection welder fitted with thyratron timer and ignitron contactors. Current was measured during welding by an air-cored toroid and integrating circuit, linked with the secondary of the machine, and recorded by means of a cathode-ray oscillograph, as described elsewhere[2].

The electrode assembly made use of tungsten-copper inserts at each projection, with individual internal water cooling, except for the $\frac{1}{2}$ in. pitch assembly, where a single insert was used, and the electrodes were accurately aligned in the machine before welding.

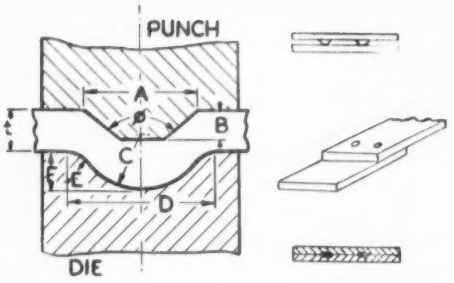
The sheet material was all supplied to specification S 84, and actual analyses are given below:

	14 s.w.g.	16 s.w.g.	18 s.w.g.	20 s.w.g.
C (per cent.)	0·050	0·06	0·050	0·050
Mn (per cent.)	0·33	0·34	0·29	0·31
S (per cent.)	0·015	0·024	0·018	0·020
P (per cent.)	0·011	0·016	0·015	0·014
Ni (per cent.)	0·048	0·05	0·042	0·040
Cu (per cent.)	0·057	0·063	0·049	0·040
Sn (per cent.)	0·008	0·009	0·008	0·008
Cr (per cent.)	Nil	Not known	Nil	Nil
Mo (per cent.)	Nil	Not known	Nil	Nil

The surfaces were free from rust.

The projection shapes used in all the tests on multiple projection welds are given in Fig. 1. For the 2-in. pitch projections, one projection was $\frac{1}{2}$ in. away from the end of the sheet, as shown in Fig. 2, and for smaller pitches the position of the centre of the triangle was maintained constant, at the same point as for 2 in. pitch. The projections were raised individually, using a fly-press and a jig to ensure accurate location of the projections. Projection height was controlled to give differences of less than 0·0005 in. between the three in any one specimen. Average height varied somewhat from specimen to specimen due to differences in sheet thickness; the maximum difference between specimens was 0·004 in., and this was not sufficient to affect the results. The positioning of the specimens relative to the machine throat is shown in Fig. 2. The working stroke of the moving head was $\frac{1}{2}$ in., the minimum which could be used while allowing specimens to be loaded and unloaded from the locating pins.

The specimens were tested for total shear-strength, and sections of welds were taken for metallurgical examination



SHEET THICKNESS IN INCHES t	Std. Proj. No.	DIMENSIONS IN INCHES A	B	C	D	E	F	ø
0.030 – 0.048	1.0	0.135	0.048	0.06	0.144	0.033	0.034	90°
0.050 – 0.075	1.5	0.158	0.056	0.07	0.168	0.039	0.040	90°
0.080 – 0.095	2.0	0.180	0.064	0.08	0.192	0.045	0.046	90°
0.100 – 0.125	2.5	0.210	0.07	0.09	0.210	0.05	0.05	90°

Fig. 1 Recommended projection dimensions.

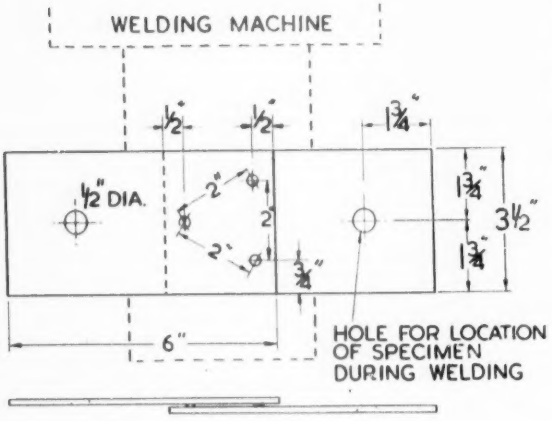


Fig. 2

to assess soundness and circularity. Consistency was assessed by calculating the coefficient of variation of strength* for each welding condition.

EXPERIMENTAL PROCEDURE

The same method was used for all gauges; initially total electrode loads of three times that for the single projection were selected, with additional tests at higher loads to extend the range of the experiments. Under all load conditions the collapse of the three projections due to mechanical pressure alone was measured and found to be less than 10 per cent. Tests were made with a range of currents and times, using a projection pitch of 2 in. The maximum current was fixed by the tendency for too rapid initial projection collapse and the minimum by the appearance of the welded joint, also the desirability of keeping welding times to 50 cycles or less had to be considered. The strengths were then plotted against time for each current used. A typical graph is shown in Fig. 3 and from these results, conditions giving satisfactory results were selected. The main basis of selection was that the group strength should be three times that of a single weld, or as near to this as possible, with the shortest time which would achieve this result for a given current.

Specimens were then welded at each of the selected conditions, at pitches of 2 in., 1½ in., 1 in. and ½ in., except in the case of 14 s.w.g. where the ½ in. pitch was omitted. Groups of eleven specimens were used, ten of which were tested in shear, and the remaining one sectioned. Weld quality was assessed by strength and consistency, surface appearance and internal structure.

The results of the tests are given in Tables II to V.

DISCUSSION OF RESULTS

The tests show that strengths of a triple-projection weld with 2 in. pitch projection can be equal to three times that of a single projection, in thickness up to 16 s.w.g. In 14 s.w.g. it is not possible to reach such a high strength, but welds can be made with 90 per cent of this value.

As the pitch is reduced, the total strength falls, an effect which is greater as the sheet thickness increases, and the three welds tend to grow towards one another. The actual strength obtained is still of good consistency. Down to 1 in. pitch, failure of the joint occurs by pulling individual slugs from the plate at each weld, but at ½ in. pitch failure is, in all the cases tested, by tearing of the sheet material from the edge of the welds. At this small pitch the three welds have grown together, forming a single large weld, and the use of three separate projections at ½ in. pitch is not a suitable preparation for welding, as an annular or Y-shaped projection would probably give better results and be easier to form.

The use of electrode loads 4½ times that for a single projection allows higher-strength welds to be made, with less danger of electrodes sticking to the material, and the welds

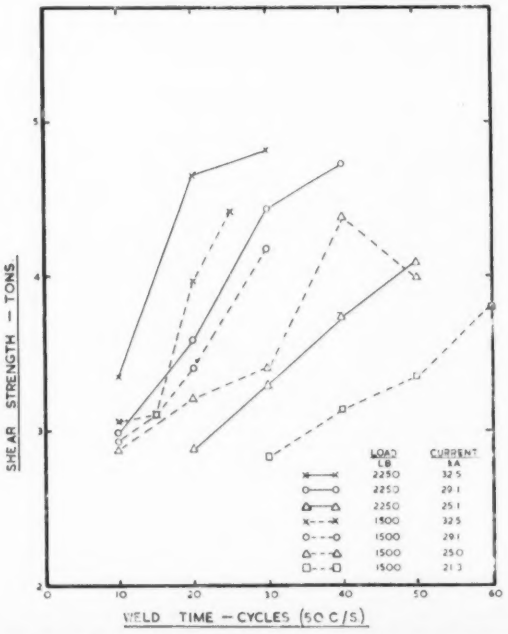


Fig. 3. Effect of welding time on strength of triple-projection welds at 2 in. pitch in 14 s.w.g. S.84 steel sheet.

* The statistical terms used in this report have been briefly explained in " Resistance welding of cold-headed bolts ", *Welding Research*, **6**, (6), 1952.

Table II.—Strengths and consistencies of triple projection welds in 14 s.w.g. S.84 steel sheet at varying pitches.

Total Electrode Load (lb.)	Welding Current (kA)	Weld Time (Cycles, 50 c/s)	Projection Pitch (in.)	Mean Shear Strength (tons)	Coefficient of Variation
2,250	31·8	20	2	4·44	2·7
	31·8		1½	4·16	2·2
	31·8		1	3·76	4·9
2,250	28·5	30	2	4·43	2·4
	28·4		1½	4·25	4·4
	28·4		1	3·85	2·4
2,250	24·9	50	2	3·54	7·7
	25·0		1½	3·64	10·7
	24·8		1	3·47	9·5
1,500	32·2	20	2	4·42	2·5
	31·0		1½	3·67	11·0
	32·3		1	3·36	9·9
1,500	28·8	30	2	4·46	3·2
	28·1		1½	4·10	8·0
	28·8		1	3·73	3·6
1,500	24·6	40	2	4·17	5·1
	24·1		1½	4·00	6·0
	24·3		1	3·57	3·7

N.B.—3 × strength of a single projection weld made under optimum conditions is 5·01 tons.

Table III.—Strengths and consistencies of triple projection welds in 16 s.w.g. S.84 steel sheet at varying pitches.

Total Electrode Load (lb.)	Welding Current (kA)	Weld Time (Cycles, 50 c/s)	Projection Pitch (in.)	Mean Shear Strength (tons)	Coefficient of Variation
2,250	34·4	15	2	4·12	1·2
	33·5		1½	3·72	4·7
	32·3		1	3·51	0·9
	*30·2		½	2·59	0·7
2,250	27·5	20	2	3·57	13·6
	27·2		1½	3·71	13·5
	27·2		1	3·43	0·8
	26·3		½	2·41	4·2
1,250	29·9	20	2	3·84	13·3
	29·3		1½	3·53	9·2
	29·6		1	3·25	5·8
	*24·4		½	2·42	—

* Current deliberately reduced to prevent the work sticking to the electrodes.

N.B.—3 × strength of a single projection weld made under optimum conditions is 4·14 tons.

are of better shape than those where a load of three times that for a single projection is used.

The actual mean projection height on a specimen is not very critical, and differences up to 0·004 in. have no appreciable effect on the weld strength *provided* the height of the individual projections in any one specimen is consistent. Differences of the order of 0·002 in. between projections on one specimen can cause considerable variations in strength. Any current shunting by burrs at the edge of the sheet, etc., will cause inconsistency and reduction of strength.

Efficient water-cooling of the electrodes is essential; otherwise, overheating will occur, causing the electrodes to stick to the material, reducing electrode life considerably. A fine finish on the electrodes, when first installed (obtained by surface grinding), is also beneficial towards an increased electrode life.

Table IV.—Strengths and consistencies of triple projection welds in 18 s.w.g. S.84 steel sheet at varying pitches.

Total Electrode Load (lb.)	Welding Current (kA)	Weld Time (Cycles, 50 c/s)	Projection Pitch (in.)	Mean Shear Srength (tons)	Coefficient of Variation
1,500	25·4	10	2	2·58	2·7
	25·3		1½	2·53	1·3
	25·0		1	2·25	2·4
	24·7		½	1·58	1·7
1,500	20·4	30	2	2·59	4·1
	20·7		1½	2·53	2·7
	21·4		1	2·14	4·7
	20·7		½	1·59	2·0
1,000	18·8	30	2	2·30	5·2
	20·0		1½	2·15	7·6
	19·7		1	2·00	2·9
	18·7		½	1·61	2·3
1,000	15·7	40	2	2·06	5·2
	17·9		1½	2·16	3·3
	16·6		1	1·88	4·1
	17·4		½	1·58	1·7

N.B.—3 × strength of a single projection weld made under optimum conditions is 2·25 tons.

Table V.—Strength and consistencies of triple projection welds in 20 s.w.g. S.84 steel sheet at varying pitches.

Total Electrode Load (lb.)	Welding Current (kA)	Weld Time (Cycles, 50 c/s)	Projection Pitch (in.)	Mean Shear Strength (tons)	Coefficient of Variation
900	23·3	10	2	1·50	8·0
	24·4		1½	1·44	4·8
	25·0		1	1·33	2·8
	23·4		½	1·02	3·5
900	20·2	20	2	1·61	8·7
	21·6		1½	1·43	3·4
	22·0		1	1·33	3·8
	20·9		½	1·02	2·6
900	17·9	30	2	1·48	5·7
	19·9		1½	1·47	6·6
	19·7		1	1·34	2·8
	17·4		½	1·05	2·5
600	20·3	20	2	1·53	4·9
	21·5		1½	1·37	5·5
	21·5		1	1·29	2·4
	20·0		½	1·00	3·5
600	17·0	40	2	1·41	9·3
	17·4		1½	1·42	6·6
	17·9		1	1·30	2·9
	16·4		½	1·03	3·9

N.B.—3 × strength of a single projection weld made under optimum conditions is 1·50 tons.

CONCLUSIONS

1. Triple-projection welds at 2 in. pitch can be made which have consistent strengths approaching or equal to three times the strength of a single-projection weld made under optimum conditions.

2. As pitch is reduced, the strength falls. The actual reduction in strength is greater as the sheet thickness is increased, though the percentage reduction is only slightly different. For 18 and 20 s.w.g., strength can be maintained with very little reduction down to 1 in. pitch, but in 16 and 14 s.w.g. the reduction at 1 in. pitch is about 15 per cent. for most conditions.

3. Projection shapes given in Fig. 1 will allow good, consistent welds to be made.

4. The best results were obtained when projection heights on a specimen were within 0·0005 in. of one another. Under production conditions it may be difficult to maintain projection heights to this accuracy and some loss in consistency can be expected.

5. Electrodes, or electrode inserts, should be very carefully aligned to ensure that they all meet uniformly when they are installed in the machine.

6. Electrodes *must* be efficiently water-cooled, or the life between dressings is reduced considerably.

7. Electrode loads three times that for a single projection can be used successfully. Higher loads, at least 4½ times that for a single projection, are desirable for the formation of sound circular welds and also should increase electrode life as sticking to the sheets is less likely to occur.

8. Any of the conditions listed in Tables II–V will give good results, but preferred conditions are contained in Table VI.

9. Distortion of the parts to be welded, especially burrs on the edges of the sheets, must be avoided, since current shunting due to contact between the sheets away from the projections will then occur, and give low and irregular strengths.

RECOMMENDED WELDING CONDITIONS

From the results of the work on triple-projection welding the following welding conditions are recommended.

Table VI

S.W.G.	Total Electrode Load (lb.)	Total Welding Current (kA)	Weld Time (Cycles, 50 c/s)	2 in. Pitch		1½ in. Pitch		1 in. Pitch	
				Group Strength (tons)	Group Strength ÷ Single Weld Strength (tons)	Group Strength (tons)	Group Strength ÷ Single Weld Strength (tons)	Group Strength (tons)	Group Strength ÷ Single Weld Strength (tons)
14	1,500	29	30	4·5	2·7	4·1	2·4	3·7	2·2
	2,250	29	30	4·4	2·6	4·2	2·5	3·8	2·3
16	1,250	30	20	3·8	2·8	3·5	2·5	3·2	2·3
	1,750	33	15	4·1	3·0	3·7	2·7	3·5	2·5
18	1,000	19	30	2·3	3·1	2·1	2·9	2·0	2·7
	1,500	21	30	2·6	3·5	2·5	3·4	2·1	2·9
20	600	20	20	1·5	3·1	1·4	2·7	1·3	2·6
	900	21	20	1·6	3·2	1·4	2·9	1·3	2·7

The coefficient of variation of strength for all the above conditions will be less than 5.
Recommended projection dimensions are given in Fig. 1.

ACKNOWLEDGEMENTS

The author wishes to thank Mr. H. E. Dixon for helpful discussions at various stages of the investigation, and Messrs. M. D. Hannah, D. H. Hillman and G. A. Phipps for carrying out the majority of the experimental work.

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